Searches for Physics beyond the Standard Model with Kaons at NA48 and NA62 at CERN

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The ratio $R_K = \Gamma(K^\pm \to e^\pm\nu(\gamma))/\Gamma(K^\pm \to \mu^\pm\nu(\gamma))$ provides a powerful probe of the structure of weak interactions. It is calculated with very high precision within the Standard Model, but corrections due to the presence of New Physics could be in a few percent range. Development of NA48/NA62 method based on test data samples of 2003-04, and the status of analysis based on a dedicated 2007 run are discussed. A proposal to measure the ultra rare decay $K^+ \to \pi^+\nu\bar\nu$ at the CERN SPS is also presented.

Introduction

The present CERN program in experimental kaon physics is represented by the NA48 series of experiments at the SPS accelerator (physics runs in 1997–2004), and its continuation NA62 (the first physics run carried out in 2007).

Several NA48/NA62 activities aiming at the search for phenomena beyond the Standard Model (SM) are discussed in the present paper. These are 1) precise testing of lepton universality by measurement of $R_K = \Gamma(K^\pm \to e^\pm\nu(\gamma))/\Gamma(K^\pm \to \mu^\pm\nu(\gamma))$ based on test data samples collected in 2003 and 2004 and a dedicated run of 2007; 2) designing an experiment to measure the branching ratio of a very rare kaon decay $K^+ \to \pi^+\nu\bar\nu$.

1 Lepton universality test by measurement of R_K

1.1 Motivation

The $V - A$ structure and lepton universality are the two cornerstones of the current description of weak interactions. The observation of the $\pi^+ \to e^+\nu$ decay at CERN in 1958 followed by later measurements of $R_\pi = \Gamma(\pi^\pm \to e^\pm\nu(\gamma))/\Gamma(\pi^\pm \to \mu^\pm\nu(\gamma))$, $R_K = \Gamma(K^\pm \to e^\pm\nu(\gamma))/\Gamma(K^\pm \to \mu^\pm\nu(\gamma))$ and $R_\tau = \Gamma(\tau^\pm \to e^\pm\nu_e\nu_\tau)/\Gamma(\tau^\pm \to \mu^\pm\nu_\mu\nu_\tau)$ provided verifications of the $V - A$ theory, confirming the suppression of electronic decay modes due to helicity conservation.

The ratio R_K can be predicted with a good accuracy in terms of fundamental parameters due to a large degree of cancellation of the hadronic uncertainties. By convention, the inner bremsstrahlung part of the $K^\pm \to \ell^\pm\nu\gamma$ process is included into R_K, while the structure dependent part (which is difficult to predict theoretically) is not. Within the SM,

$$R_K = R_{\rm tree}(1+\delta R_{\rm QED}) = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta R_{\rm QED}) = (2.477 \pm 0.001) \times 10^{-5},$$

where $\delta R_{\rm QED} = -3.8\%$ is an electromagnetic correction [2]. The factor $(m_e/m_\mu)^2$ accounts for the helicity suppression of the K_{e2} mode.

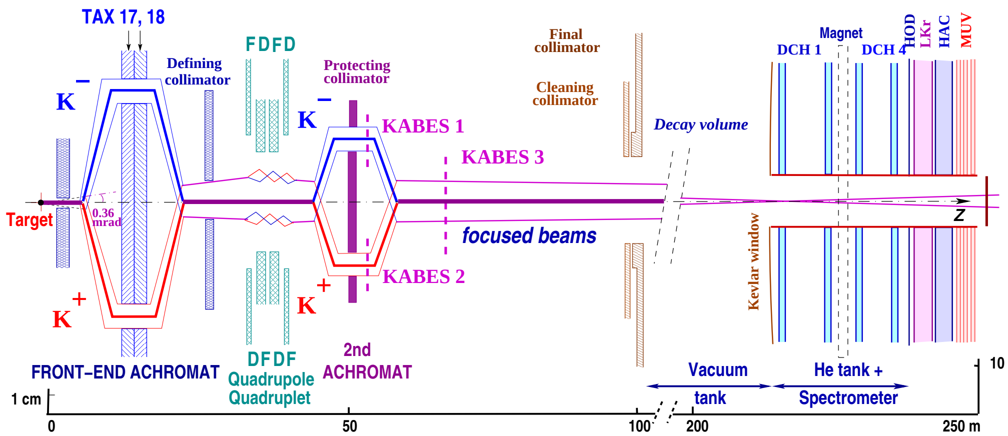

Figure 1: Schematic lateral view of the NA48/2 beam line (TAX17,18: motorized beam dump/collimators used to select the momentum of the K^+ and K^- beams; FDFD/DFDF: focusing set of quadrupoles, KABES1–3: kaon beam spectrometer stations), decay volume and detector (DCH1–4: drift chambers, HOD: hodoscope, LKr: EM calorimeter, HAC: hadron calorimeter, MUV: muon veto). Vertical scales differ in the two parts of the figure.

A recent theoretical study [3] pointed out that, due to the helicity suppression of R_K in the SM, lepton-flavour violating effects arising in super-symmetric extensions can induce sizable violations of the $\mu - e$ universality, shifting R_K from the SM value by a relative amount that can be in the percent range, without contradicting any other presently known experimental constraints. The current world average $R_K = (2.45 \pm 0.11) \times 10^{-5}$ [4] is compatible with the SM prediction, being however far from its current level of accuracy.

1.2 Development of NA48/NA62 experimental method

The NA48 program dedicated to study of the charged kaon decays, known as the NA48/2 experiment, is based on the physics runs of 2003–04. The experiment was designed to excel in charge asymmetry measurements [5], and is based on simultaneous K^+ and K^- beams produced by 400 GeV/c primary SPS protons interacting with a beryllium target. The layout of the beams and detectors is shown schematically in Fig. 1. Charged particles with momentum (60 ± 3) GeV/c are selected by an achromatic system of four dipole magnets with zero total deflection (‘achromat’), which splits the two beams in the vertical plane and then recombines them on a common axis.

The beams then enter a fiducial decay volume housed in a 114 m long cylindrical vacuum tank. The decay volume is followed by a magnetic spectrometer consisting of four drift chambers, a trigger scintillator hodoscope, a liquid krypton electromagnetic calorimeter, a hadron calorimeter, and a muon detector. Further details on the experimental setup can be found elsewhere [6].

During a part of the 2003 run (4 weeks of data taking), a two level K_{e2} trigger chain suitable for R_K measurement was implemented along with the main triggers. The first level (L1) consisted of a time coincidence of hits in the two planes of the HOD (so called Q_1 signal) with an energy deposition of at least 10 GeV in the calorimeter. The second

level (L2) consisted of a requirement that the missing mass m_X computed using the track momentum measured by the spectrometer in the hypothesis of $K \to \pi X$ decay is below the π^0 mass. The K_{e2} trigger was downscaled by a factor ranging from 20 to 40 during the data taking. The $K_{\mu 2}$ trigger consisted of the Q_1 condition only downscaled by a factor of 10^4.

The 2003 data sample of 4670 $K^{\pm}_{e2}$ candidates with 12% estimated background was used to establish the analysis strategy. However the data quality appeared to be affected by high inefficiency of the L2 trigger, measured to be about 15% (while the L1 inefficiency was measured to be below 1%). As a consequence, the uncertainty of the 2003 result received a $\delta R_K/R_K = 0.8\%$ contribution from the L2 trigger inefficiency.

To overcome the above limitation, a dedicated 56 hour run was taken in 2004 with a simplified K_{e2} trigger consisting of the L1 part only without downscaling, the main trigger chains disabled, and beam intensity reduced by a factor of 4 with respect to the nominal value. Analysis of those data led to further refinements of the experimental approach.

Event selection is based on (1) kinematic criteria: $K_{\ell 2}$ candidates are required to have squared missing mass $M^2_{\rm miss}(\ell) = (P_K - P_\ell)^2$ compatible to zero, where P_K, P_ℓ ($\ell = e, \mu$) are 4-momenta of kaon (beam average assumed) and lepton (electron or muon mass assumed); (2) particle identification based on the ratio E/p of track energy deposition in the calorimeter to track momentum: particles with $E/p > 0.95$ ($E/p < 0.2$) are identified as electrons (muons). The use of the identification criteria necessitates a detailed study of the calorimeter response: particle identification probabilities are measured with the data.

Analysis of the 2004 data sample containing 3930 K_{e2} candidates with 14% estimated background was focused on the technique of background subtraction in the K_{e2} sample. The major contribution (12%) is due to $K_{\mu 2}$ decays with muons releasing almost all their energy in the calorimeter by 'catastrophic' bremsstrahlung. It contributes at high lepton momenta only, in the region of poor $K_{e2}/K_{\mu 2}$ kinematical separation. Its subtraction requires a measurement of the probability $P(\mu \to e)$ of the (rare) muon misidentification as electron due to having $E/p > 0.95$, which requires selection of a very clean muon sample free of electron admixture. In 2003–04 data taking conditions, only the kinematical region of low lepton momentum $p < 35$ GeV/c, i.e. good $K_{e2}/K_{\mu 2}$ kinematical separation, in which kinematical selection of a pure $K_{\mu 2}$ sample is possible, is accessible for such measurement. It was measured in this region: $P(\mu \to e) = 4 \times 10^{-6}$. However theory suggests growth of 'catastrophic' bremsstrahlung cross section as a function of muon momentum [7], which impedes reliable $K_{\mu 2}$ background subtraction. As a consequence, the precision of the 2004 result is limited by a corresponding uncertainty of $\delta R_K/R_K = 1.6\%$.

1.3 A dedicated $K^{\pm} \to e^{\pm}\nu$ run in 2007

A dedicated K_{e2} run of the NA62 experiment was carried out in June–October of 2007 with the aim of reaching an improved level accuracy of better than $\delta R_K/R_K = 0.5\%$. The data taking conditions were optimized with respect to 2004 using the past experience as follows.

- $M^2_{\rm miss}$ resolution was improved by using narrow band $K^{\pm}$ beams (2% RMS vs 3% in 2003–04), and larger spectrometer magnet momentum kick (263 MeV/c vs 120 MeV/c in 2003–04, reaching lepton momentum resolution of $\delta p/p = 0.47\% \oplus 0.020\% p$, p in GeV/c). Expected $K_{\mu 2}$ contamination in K_{e2} sample is 7% vs 12% in 2003–04.

- Selection of pure muon samples in the whole analysis muon momentum range was made possible by installing a $\sim 10 X_0$ thick lead wall (absorbing a large fraction of

electron, but not muon, energy deposition) between the two planes of the scintillator hodoscope covering $\sim 20\%$ of the geometric acceptance. Preliminary measurements of $P(\mu \to e)$ confirm the predicted momentum dependence of this quantity.

- A number of runs with special conditions were carried out to address the measurements of lepton misidentification probabilities, and the background induced by the beam halo.

About 1.1×10^5 K_{e2} candidates with $< 10\%$ background were collected, data analysis started.

2 A proposal to measure BR($K^+ \to \pi^+\nu\bar{\nu}$) at CERN

The $K^+ \to \pi^+\nu\bar{\nu}$ decay is a FCNC process with the SM branching ratio computed to be $(7.83 \pm 0.82) \times 10^{-11}$ [8]. Its unique theoretical cleanness owes to the possibility of parameterizing the hadronic matrix element via the experimentally well known BR($K^+ \to \pi^0 e^+\nu$); theoretical uncertainty is largely due to those of the CKM matrix elements.

The NA62 proposal to collect ~ 100 decays with 10% background in 2 years of operation, as required to match the theory precision, is based on the existing NA48 kaon beam line and infrastructure. The R&D started in 2006, and data taking is foreseen to start in 2011. Decay in flight technique is chosen, reaching an acceptance of 10%; the beam line is required to provide 10^{13} kaon decays from unseparated beam with 6% kaon fraction in about 200 days of data taking.

The experimental signature of the $K^+ \to \pi^+\nu\bar{\nu}$ decay is a single reconstructed track in the detector downstream the decay volume in time coincidence with a kaon measured by the upstream beam tracker. Kinematic selection is performed using K momentum measurement by a silicon pixel detector in the beam operating at rate of 800 MHz, and π momentum measurement by a magnetic spectrometer consisting of straw chambers operating in vacuum.

In addition to kinematic rejection (which provides large rejection factors for $K_{\mu2}$, $K_{2\pi}$ and $K_{3\pi}$ decays, but is not sufficient for background suppression), the following techniques are used to provide redundancy. Particle identification is based on CEDAR differential Cherenkov counter [9] for kaons, and RICH detector for pions. A series of photon detectors are used to provide a hermetic photon veto with an inefficiency of $\sim 10^{-5}$: these are ring shaped scintillator fibre calorimeters at large angles of 10–50 mrad, the existing NA48 liquid crypton calorimeter at 1–10 mrad, and a set of small angle vetoes based on shashlyk technology at low angles. Prototypes of the new detectors were successfully tested at CERN and Frascati in 2006–2007; a series of further tests is foreseen in 2008.

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